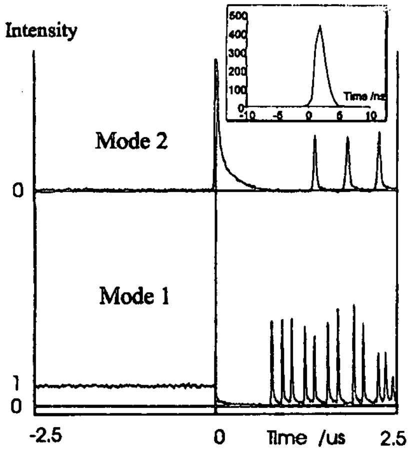

CThBB3 Fig. 2. Intensity fluctuations in mode 1 (lower) and mode 2 (upper trace). The intensity of the giant pulse at $t = 0$ in the second mode is >100 times greater than the following relaxation oscillations. Inset shows a typical giant pulse.

sorption or gain transition. Modes at either side of gain center will see guiding or antiguiding associated with the transverse variation of this refractive-index change.[3] The first mode to oscillate in our laser is further from the gain center than its main competitor but initially competes successfully because of its smaller mode volume. Above threshold, the residual gain, left from spatial hole burning, will maintain an antiguiding effect for the lower-frequency second longitudinal mode. As the second mode exceeds its threshold condition, it will deplete this gain and find itself well above its new threshold. The stored residual gain, combined with the larger mode volume for the second mode, yield a giant pulse when threshold is reached. The change from the positively guided first mode to the second mode gives a decrease in output beam divergence.

We have constructed a simple model to include the above effect in determining the stability of a microchip laser. The results of this model are presented in comparison to the observed experimental work, to show how the effects of gain-related cavity stability can cause self-Q-switching in an $Nd:YVO_4$ microchip laser.

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CThBB4 **5:15 pm**

Low-voltage electro-optic Q switching of 1.06-μm microlasers by PLZT

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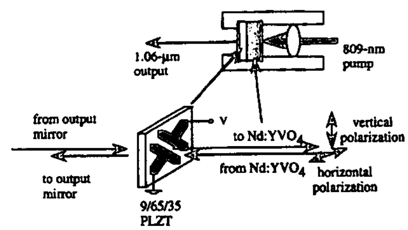
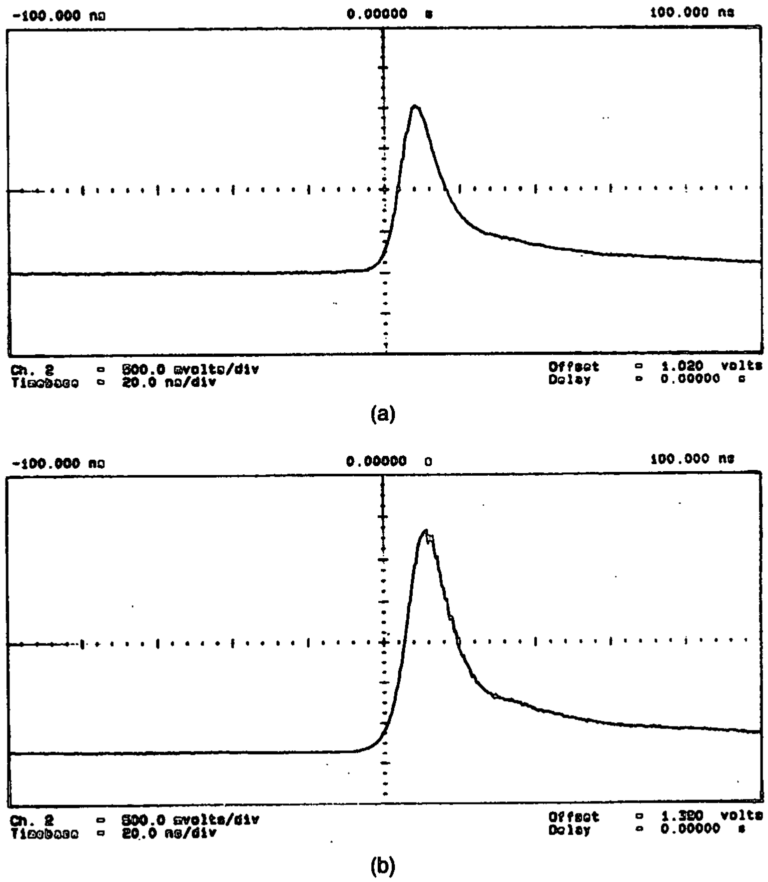
Q switching utilizing saturable absorption does not require an external driver; however, the power output and repetition rate are not stable. Acousto-optic or electro-optic (EO) Q switching exhibits much stable performance but requires high rf power or kilovolt voltage due to the small modulation efficiency of KDP and $LiNbO_3$. In this paper, we present an innovative lead lanthanum zirconated titanate (PLZT)-based EO Q switch. Due to its large EO coefficient, a drive voltage of only 300 V to Q switch a 1.06-μm $Nd:YVO_4$ laser was measured.

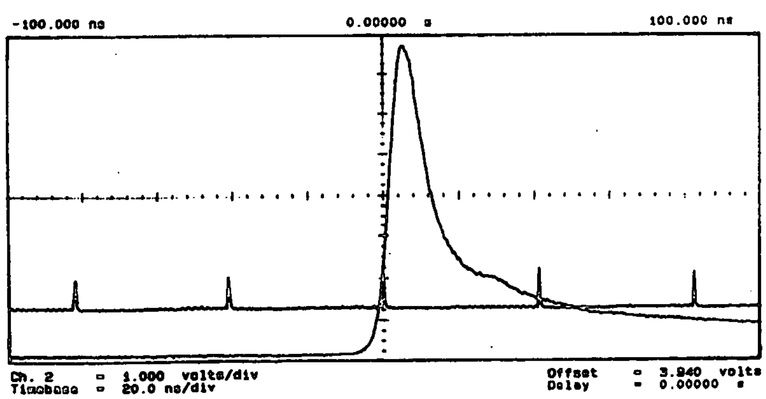


CThBB4 Fig. 1. Schematics of the PLZT EO Q-switched $Nd:YVO_4$ microlaser.

By doping PZT with lanthanum, the ferroelectric ceramics becomes transparent.[1,2] PLZT with an La/Zr/Ti ratio of 9:65:35 is known to process a slim-looped quadratic EO effect with a coefficient equivalent to two orders of magnitude larger than $LiNbO_3$. Such a large EO effect and its ~100-ns response speed offer a potential to substantially lower the Q-switch voltage, reducing the packaging size and laser cost. Plotted in Fig. 1, the cavity con-



CThBB4 Fig. 2. Q-switched laser pulses of 1.06-μm with a pump power of 1 W and a repetition rate of 1 kHz (a) and 10 kHz (b). The cavity on time for both cases is 500 ns. The time scale of the plot is 20 ns/cm.



CThBB4 Fig. 3. Q-switched laser pulses of 1.06 μm with the addition of a quarter-wave plate. The voltage pulse width and the repetition rate are 200 ns and 10 kHz, respectively.

sists of a 1-mm-thick, 1.1% Nd-doped YVO_4, a 375-μm-thick PLZT, and a 15% transmitted output mirror; the back mirror of the cavity is formed by coating the back facet of the YVO_4 99.8% reflecting to 1.06 μm and 90% transmitting to 809 nm. When no voltage is applied to the Pt electrodes deposited on both sides of the PLZT, the horizontally (c axis of YVO_4) polarized 1.06-μm emission passes the homogeneous PLZT undisturbed, and the laser is "on." When a voltage is applied, the randomly arranged dipoles of PLZT are aligned to the electric field 45° oriented with the horizon, inducing a birefringence according to $\Delta n \equiv n_e - n_o = -\frac{1}{2} n^3 R E^2$, where n and R are the zero-field refractive index and quadratic EO coefficient, i.e., 2.31 and 3.8×10^{-16} $(m/V)^2$, respectively, and E is the electric field. When the induced birefringence adds a π-phase shift onto the passing emission (two passes per round trip), the polarization of the emission rotates to vertical direction when it comes back to the laser crystal, experiencing a zero amplification, and the laser is "off."

Figure 2 shows the Q-switching performance for a pulse repetition rate of 1 and 10 kHz, with a 1-W cw Ti:sapphire used as the pump. The cavity on time was 500 ns for both cases. Q switching was achieved with a shape rise and a pulse width of 12 ns at 1 kHz and 14 ns at 10 kHz. The average output power was 80 and 110 mW, corresponding to a peak power of 6.7 and 0.79 kW/pulse, respectively. The drive voltage was ~310 V for both cases.

In the above cases, a voltage has to be applied to turn off the laser. To reverse the polarity, a quarter-wave plate was added to the cavity. The 11-ns Q switching is shown in Fig. 3, with a pulse repetition rate of ~10 kHz and a voltage pulse width of 200 ns. The chain of Q-switched laser pulses is also shown in the inset of Fig. 3. As expected, the laser output power was stable from pulse to pulse, and the timing of laser pulses was well controlled by the voltage driver. Higher-power efficiency will be available with further improvement on the polishing quality of the PLZT surfaces and on the reduction of the PLZT body scattering.

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CThBB5 **5:30 pm**

Fundamental investigations of modulated microchip laser arrays (MLAR) with frequency doubling

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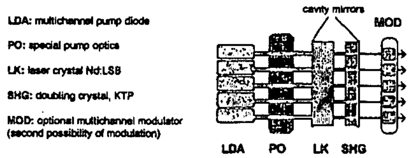
This laser-array project with frequency doubling is attractive because of the possibility of modulating each element of the array separately. Complicated scan optics are no longer needed, and the small array takes up space. The working speed is significantly accelerated through use of 24 emitters simultaneously.



CThBB5 **Fig. 1.** One-dimensional diode pumped frequency-doubled microchip array, 24 channels.

Possible applications are reprography, rapid prototyping, image processing, and multichannel measurements.

The goals of the project are a fundamental investigation of the interactions of closed-spaced microchip elements, a search for limits of miniaturization, testing of different concepts, an investigation of beam characteristic, and modulation.

A recently realized system (Fig. 1) consists of the multiemitter laser diode, the pump optic, laser crystal, and frequency doubler crystal. The laser crystal and doubler crystal are suitably coated to build up the resonator. The length of the resonator is variable to vary the beam characteristic. For the first time, Nd:LSB is used for a microchip laser array.[1–6] This has several advantages. Because of the modulation in the current of the single emitter of the laser diode, the temperature of the laser diode varies; therefore, the wavelength of the laser diode also changes. Nd:LSB reduces temperature-induced power fluctuations in the microchip laser array because it has a broad absorption peak of several nanometers. Another advantage is the small absorption length of Nd:LSB. This is advantageous because of the divergence in the pump focus. The pump spots are closed spaced and are not allowed to overlap, otherwise one gets strong coupling of the laser, and independent modulation becomes impossible.

An important parameter for designing a laser diode with independently addressable emitters[7] is the separation between the emitters. If this separation is too small, strong coupling inhibits separate modulation. For the purpose of the experiments, six single 1-W laser diodes were made. The light was coupled in a 110-μm-diameter fiber. Because of optical losses in the fiber coupler and in the pump optics, the effective pump power was ~600 mW. The images of the six fiber ends were pictured 1:1 with specially designed optics on an Nd:LSB crystal. The power of the Nd:LSB laser was ~120 mW/channel. Because of the small absorption length, the thermal lenses are very strong on the order of several 100 Dpt/W. The experimental result was that the minimum center distance of the fibers for uncoupled lasers has to be at least 300 μm. In this case, interference in the far field vanishes.

With this experience, a special 15-W laser-diode array with 24 emitters, a period of 400 μm, and width 200 μm was designed by Jenoptik Laserdiode. Individual current modulation is possible. The pump power per channel is ~600 mW. The divergence in the slow axis is 15° and in the fast axis 100°. A cylindrical lens in front of the emitters reduces the divergence. A special power supply with 24 channels was designed for the laser diode with 24 independently operating emitters. The pump optics that pictured the emitters 1:1 fulfills high demands on the quality of the image; otherwise, the spots on the crystal would overlap and strong coupling would occur. A KTP crystal is used for frequency doubling. In the first experiments with 8 emitters working simultaneously, we managed to get an output power at 531 nm of ~50 mW/channel. The laser diode and the Nd:LSB crystal were indirectly water cooled. With other crystals, emission in the blue region is possible.

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CThBB6 **5:45 pm**

Whispering-gallery modes in microring lasers made from conjugated polymers

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Stimulated emission has been reported in various semiconducting conjugated polymers, and the prospect of compact electrically pumped polymer lasers is exciting. Very recently, we were able to obtain unambiguous features of optically pumped laser emission from a poly[2,5-bis-(2′-ethylhexyloxy)-p-phenylenevinylene] (BEH-PPV) film contained in a high-finesse Fabry–Perot cavity.[1] Independent measurements revealed large optical gain that enables lasing in very small volumes, assuming that the suitable feedback is provided. Microcavities are easy to integrate and have the advantage that high Q values can be obtained even in very small and controllable mode volumes in which the current

Q-Switching of Er:YAG (2.9 μm) Solid-State Laser by PLZT Electrooptic Modulator

Maris Ozolinsh, Karl Stock, Raimund Hibst, and Rudolf Steiner

Abstract—**Small-size PLZT 8.5/65/35 ceramic modulators with the length of 4–6 mm are used to obtain Q-switched pulses of the Er:YAG lasers—the pulsewidth 150 ns, energy of the single pulse up to 5 mJ, if followed by a number of the small-intensity postlasing pulses—the total energy of pulses is up to 10 mJ.**

Index Terms— **Electrooptic PLZT ceramics, electrooptic switches, Er:YAG lasers, Q-switched lasers.**

I. Introduction

THE WAVELENGTH of Er:YAG laser radiation (λ = 2.94 μm) matches a pronounced absorption band of water. As typical for solid-state lasers, the Er:YAG laser emits spikes which form an envelope with duration 150–800 μs depending on pumping conditions. The small penetration depth of the radiation (little more than 1 μm in water) and the high intensity of the Er:YAG laser pulses promote effective ablation of soft and hard human tissues (the latter group is of special interest for dentistry) with minimum inevitable destruction of the area closed to the treated location [1]. However, the relatively long rise time and especially decay of the Er:YAG laser pulse envelope can cause heating effects inevitable by ablation. Two methods can be used to solve this problem. Shortening of the rise and decay times can be accomplished by additional extracavity amplitude modulation. In [2], we reported on the use of PLZT ceramics electrooptic modulators in order to cut out Π shape segments from the Er:YAG pulse envelope. The other way is applying the Q-switching technique, which allows concentrating a significant part of the pump energy into very short high-intensity laser pulses. Q-switching is widely applied with such solid-state lasers as Nd:YAG, alexandrite, and others. Attempts to obtain Q-switched Er:YAG laser pulses have been less successful. Various modulation techniques have been used and the following results have been obtained: 1) the mechanically rotating mirror—pulse energy 16 mJ, duration 850 ns [3]; 2) electrooptic Q-switching by the use of $LiNbO_3$ single crystal modulators—the energy of a single pulse without pre- and postlasing pulses 4 mJ, duration 400 ns [3], the same with the Er:YAG amplifier—6 mJ and 300 ns [4]; and 3) acoustooptic Q-switching—pulses of energy 9.3 mJ, duration 100 ns [5]. Q-switching is realized also by using of other techniques (saturable absorbers, full total internal reflection—FTIR modulators) [5]–[8]. However, the results obtained by Q-switching for the Er:YAG laser (the same concerrns related lasers as on Er:YSGG, etc.) differ qualitatively from those of the Nd:YAG laser. There are two basic reasons which do not allow giant intensity short Er:YAG laser pulses using Q-switching to be obtained as compared with the Nd:YAG laser.

The first is a relatively short life time at the upper level $\tau_1 \approx 100$ μs, which does not allow the population inversion to be held at a high level long enough, and Q-switching must take place shortly after the pumping rate begin to decrease [3]. The second is a low single-pass gain. Due to that, a great number of round trips is needed to form the pulse, and the corresponding pulse build-up time is little less than 1 μs [3].

PLZT ceramics are transparent in the mid- and near-infrared spectrum ranges and show a pronounced quadratic electrooptic effect that has allowed construction of small-size electrooptic switches for Er:YAG laser radiation modulation [2]. As compared to $LiNbO_3$ single crystals, the switching speed of PLZT ceramics is much lower, nevertheless in the submicrosecond range, and is comparable with the pulse build-up time of an Er:YAG laser pulse. This paper reports on the first attempts to accomplish Q-switching of Er:YAG lasers by the use of PLZT ceramic modulators.

II. Experimental

We have carried out our experiments with the commercial ERY-1 ISKRA *elektrooptika* laser. The Er:YAG crystal (with 50% Er) had a length of 3.5 in and a diameter of 4 mm. The distance between the high reflective spherical rear mirror (radius 2 m) and the plane front mirror (reflectance 90%) was 24 cm. In order to obtain a linearly polarized emission, we placed a PLZT plate at the Brewster angle in the cavity as reported in [2], which gives a degree of polarization of light close to 100%. Two different PLZT modulators were used as the Q-switches. The first one had a length of 6 mm and a distance between electrodes of 4 mm. The modulator had no antireflective coatings, and the transmission of the modulator was $\approx$60%. It was placed perpendicular to the laser beam between the front mirror and the crystal, thereby minimizing losses (at the low-loss state the optical losses were caused mainly by the Fresnel reflections on the surfaces of the modulator $\approx$62% and by losses in output coupling $\approx$6%). The other PLZT modulator had a length of 3 mm, a distance between electrodes of 6 mm, and was placed at the Brewster angle between the rear mirror and the crystal.

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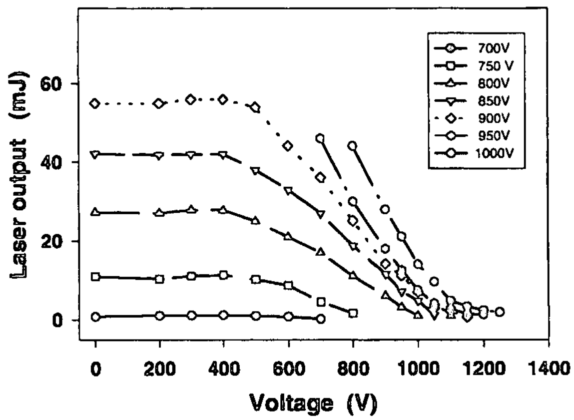

Fig. 1. Q-switch voltage needed to suppress laser oscillations at various pumping rates.

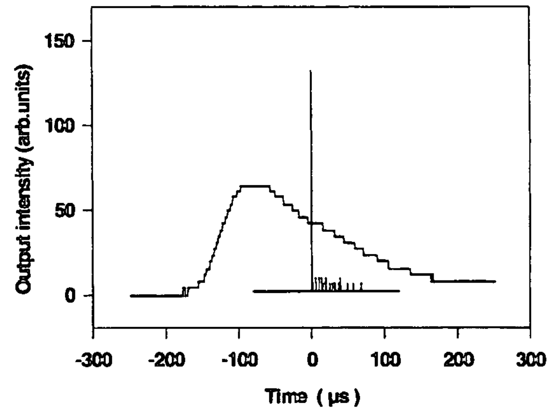

Fig. 2. Laser flashlamp pulse and Q-switched pulses in multipulse lasing mode.

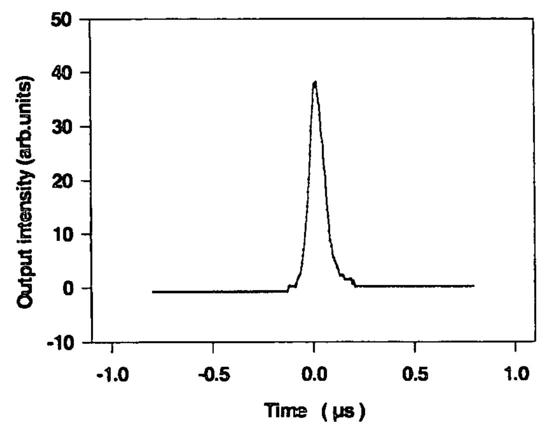

Fig. 3. Pulse shape of the single Q-switched pulse.

Both modulators were made of PLZT 8.5/65/35 and were operated at temperatures $T = 40$ °C–60 °C (for more details on the properties of PLZT 8.5/65/35 in the infrared, see [2]). Experiments were carried out according to such scheme to give answers to the following questions.

1) Can the laser of such configuration emit radiation with the open-state PLZT Q-switch in the cavity, which brings additional 62% losses due to reflection? What is the dc voltage needed to suppress the laser oscillations?
2) What are the characteristics of Q-switching (single or multilasing, pulsewidth, energy, pulse build-up time) at various conditions (pumping rate, Q-switch triggering)?
3) What happens when the "high" loss PLZT Q-switch is replaced with another one placed at the Brewster angle?

III. Results

The laser continued to operate in spite of significant additional losses brought by inserting the PLZT modulator in the cavity perpendicular to the optical axis. With the modulator inserted, the threshold pumping voltage was 700 V. This value corresponds to a 20% increase of the laser flashlamp power. In order to cause a maximum loss in the cavity, the quarterwave voltage $U_{\lambda/4}$ must be applied to the modulator. For the 6-mm-thick modulator at a working temperature of 50 °C, the value of $U_{\lambda/4}$ exceeds 1500 V. Fig. 1 shows the dependence of the laser output on the value of the dc voltage applied to the modulator at various pumping flashlamp voltages U_p. We have carried out experiments mainly with pump voltages lower than 800 V, in order not to damage the laser crystal.

The optimum delay of Q-switching according to the beginning of the pumping pulse was within 170–200 μs. Fig. 2 shows the pump pulse and emitted Q-switched pulses; one can see the first high-intensity Q-switched pulse and a number of postlasing pulses. Varying the delay of Q-switching, we have obtained the satisfactory single-pulse lasing—if the pump voltage was not too high, and if the Q-switch at the "high" loss state was not maximally closed. For such almost single-pulse lasing, the energy of pulses was 3–4 mJ. The pulsewidth of the Q-switched pulses was within the range of 150–200 ns (Fig. 3). Further increases of the pump voltage led to emitting multiple pulses, mainly postlasing pulses. The total energy released per one pump pulse was up to 10–11 mJ (at a pump voltage of 770 V, the corresponding value of the free run laser output was 17 mJ), however, with the energy of the most intense pulse not exceeding a value of 4 mJ. The sequence of pulses at such conditions could be quite various, the crystal could emit the most intense pulse as the first one, or the most intense pulse could be proceeded by one or sometimes two pulses with a significantly smaller intensity. The prelasing was more likely when the voltage applied to the Q-switch during the cavity high-loss state was increased much over the value needed to suppress the free-running laser oscillations. That could be due to the increase of the time needed for the PLZT Q-switch to switch to the low-loss state of the cavity for the case of higher Q-switch voltages at the high-loss state. Fig. 4 shows the dependence of the pulse build-up time τ_b (the time interval between the Q-switching instant and the maximum of the first high-intensity pulse) on the voltage applied to the Q-switch at the cavity high-loss state. The sharp and more than two times increase of the value of τ_b for the Q-switch voltages more than 1350 V obviously can be explained by the fact that the measured value corresponds to the second pulse proceeded by a too-small-to-be-observed prelasing pulse.

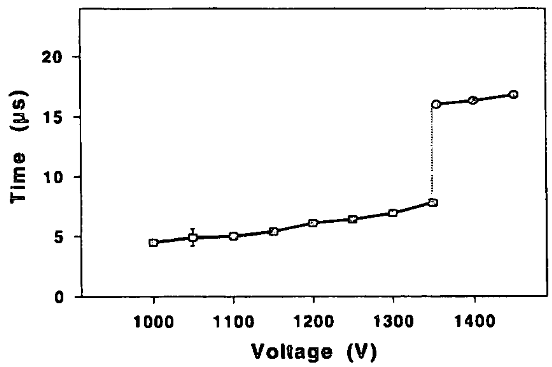

Fig. 4. Pulse build-up time versus Q-switch voltage applied at cavity high-loss state.

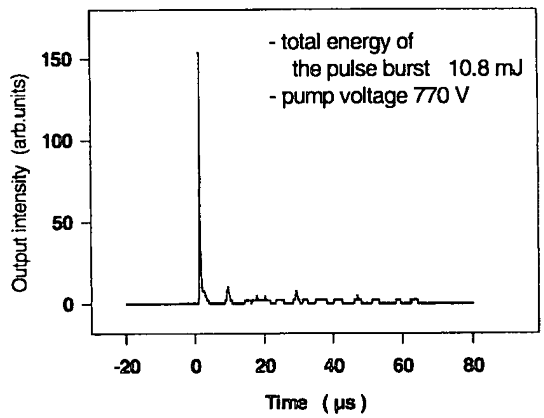

Fig. 5. Laser output with PLZT Q-switch aligned at the Brewster angle.

The obtained results allow us to make the following conclusions. In spite of the high reflection losses, the electrooptic elements of PLZT without antireflective coatings can be placed in the cavity of the Er:YAG laser. Q-switching by use of the previously mentioned technique does not allow the most optimum results. The high losses determine a great value of the build-up time τ_b—more than 5 μs—and prevent higher intensity single pulses to be obtained. A long transient from the high-loss to the low-loss state of the cavity causes multipulse lasing.

Placing the other PLZT modulator in the cavity aligned at the Brewster angle allowed us to avoid significantly the first of these negative factors. The small size of the Q-switch and especially the small optical path (thickness of the modulator 3 mm) allow building a Q-switch in the cavity without any changes in the construction of the laser, in spite of the shift of the optical axes. The results obtained were quite promising. The pulse build-up time τ_b decreases to 1.5 μs, and single-mode lasing with higher pulse intensities was accomplished. Nevertheless, the increase of the pumping voltage in order to obtain pulses with a higher energy led to multipulse lasing. Fig. 5 shows an example of the sequence of pulses typical for such Q-switching. The postlasing pulses in this case had significantly smaller intensities as compared with the case of the perpendicularly oriented Q-switch.

Taking into account that the basic problem with obtaining higher intensity single Q-switched pulses is the short lifetime at the upper level τ_1, the most promising approach would be to accomplish the cutting of a small duration (comparable with the pulse build-up time 1.5 μs) low-cavity-loss window synchronized with the pumping pulse, which seems quite possible by the use of PLZT ceramics.

IV. Conclusion

The first results of the use of PLZT ceramic electrooptic modulators for Q-switching of the Er:YAG laser are reported. In spite of some PLZT ceramics disadvantages, the great electrooptic effect in PLZT allows attractively small elements to be constructed for this purpose. Using Q-switches with antireflective coatings, and techniques allowing the fast and time-resolved switching, would significantly improved the results obtain by the use of PLZT modulators for Q-switching of the Er:YAG laser.

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